XP-002179951

PD: 00-00-1987
P: 116-125
(10)

Table 2. Densities of Cold Worked Aluminum-Magnesium Alloys

Alloy	Density: Annealed g/cm³	Annealed lb/in.³	Cold rolled, 80% g/cm³	Cold rolled, 80% lb/in.³	Change, %
Al	2.7011	0.97583	2.7006	0.97565	−0.018
Al-1 Mg	2.6883	0.97121	2.6877	0.97099	−0.022
Al-2.4 Mg	2.6696	0.96445	2.6687	0.96413	−0.034
Al-4.4 Mg	2.6450	0.95556	2.6430	0.95484	−0.076

Source: Courtesy of Aluminum Company of America.

ter than strain-hardened alloys. But when applied stresses are very small and mechanical hysteresis is not a factor, strain hardening may increase damping.

The effects of strain hardening on the chemical properties of aluminum are usually quite small. Substantial effects can often be traced to secondary reactions from the effects of strain hardening on the metallurgical structure of the alloy. Aluminum alloys are expected to react with specific environments at an increased rate, because of the greater strain energy stored in the metals by deformation. But, evidence shows that cold work has little effect on the corrosion resistance of most aluminum alloys in a variety of exposure conditions.

In some special situations, the corrosion resistance of certain aluminum alloys may be decreased by cold working (Chapter 7 in this Volume). Cold working can cause residual tensile stresses and consequent stress-corrosion cracking of some heat treatable alloys exposed to corrosive environments. Cold work also may induce or accelerate grain boundary precipitation in the non-heat treatable aluminum-magnesium alloys; alloys containing more than 4% magnesium may thereby become susceptible to stress-corrosion cracking. Generally, only long aging at room temperature or heating at elevated temperatures produces sufficient grain boundary precipitation to induce susceptibility to stress-corrosion cracking. However, in most commercial aluminum-magnesium alloys, the amount of cold work is intentionally limited; special corrosion-resistant tempers are recommended.

ANNEALING

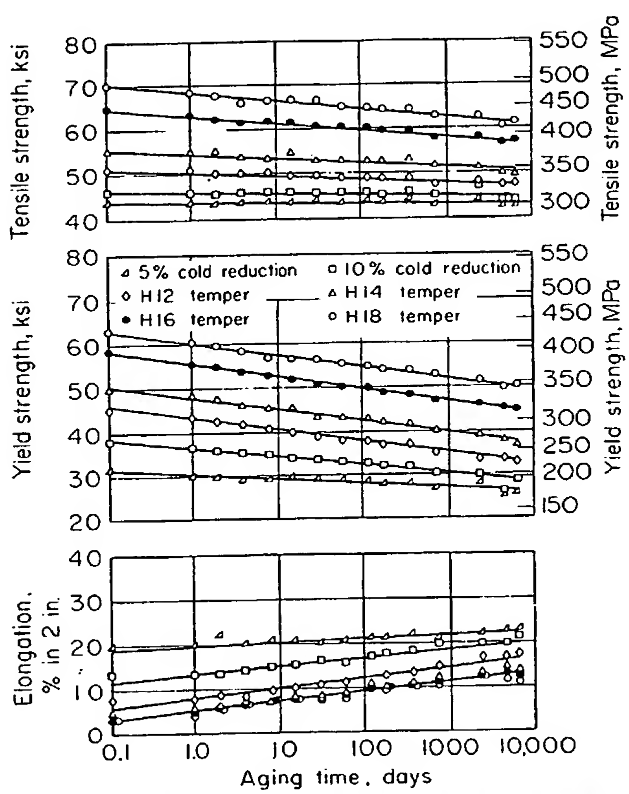
The dislocation structure resulting from cold working of aluminum is less stable than the strain-free, annealed state to which it tends to revert. In zone-refined aluminum, this reversion may take place at room temperature. Lower purity aluminum and commercial aluminum alloys undergo detectable structural changes only with annealing at elevated temperatures. Accompanying the structural reversion are changes in the various properties affected by cold working. These changes occur in several stages, according to temperature or time, and have led to the concept of different annealing mechanisms or processes. The first of these, occurring at the lowest temperatures and shortest times of annealing, is known as the recovery process.

Recovery. Structural changes occurring during the early stages of the

techniques. Evidence obtained by x-ray diffraction and with the transmission electron microscope shows that during recovery, dislocations are greatly reduced in number and often rearranged into a cellular subgrain structure. Figure 9 shows this sequence of recovery in an Al-5% Mg alloy. This process of recovery is sometimes referred to as polygonization. With increasing time and temperature of heating, polygonization becomes more nearly complete and the subgrain size gradually increases. In this stage, many of the subgrains have boundaries that are completely free of dislocation tangles.

The decrease in dislocation density caused by recovery-type annealing produces a decrease in strength and other property changes. The effects on the tensile properties of 1100 alloy are shown in Fig. 11. At temperatures through about 230 °C (450 °F), softening is accomplished by a recovery mechanism. The process is characterized by an initial rapid decrease in strength and a slow, asymptotic approach to a lower strength, the higher the temperature. Other aluminum alloys behave similarly, although the response to recovery annealing varies with composition. The aluminum-magnesium alloys show a particularly marked response.

Recovery annealing is also accompanied by changes in other properties



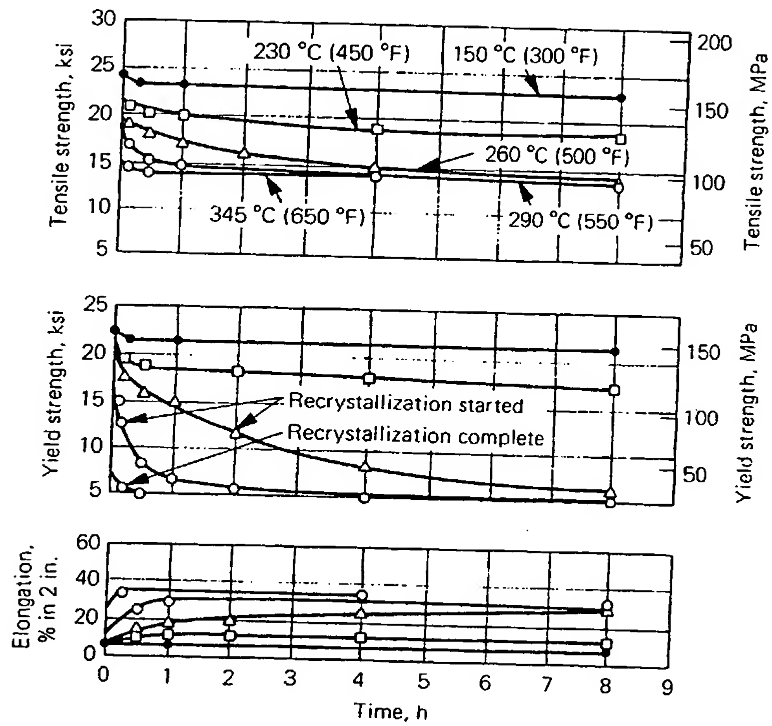


Fig. 12. Age softening of strain-hardened Al-6% Mg sheet. (Courtesy of Aluminum Company of America)

of cold worked aluminum. Electrical conductivity increases, while x-ray line broadening, internal stresses, and stored energy decrease. The relative change is not the same for each property. Generally, some property change can be detected at temperatures as low as 93 to 120 °C (200 to 250 °F). The change increases in magnitude with increasing temperature. Complete recovery from the effects of cold working is obtained only with recrystallization.

Strain-hardened aluminum-magnesium alloys are a special commercial problem, because they tend to age soften at room temperature. Figure 12 shows this effect for an Al-6% Mg alloy. Age softening increases with increasing cold work and magnesium content.

Electron micrographic studies of highly strained aluminum-magnesium alloys reveal no change in dislocation density during age softening. Apparently, strain energy is released through the interaction and relaxation of tangled dislocations without causing an obvious decrease in their numbers.

Because age softening complicates the guaranteeing of minimum properties for strain-hardened aluminum-magnesium alloys, industry practice is to accelerate age softening and increase ductility by heating the alloy briefly from 120 to 175 °C (250 to 350 °F). The properties achieved are quite stable. These strain-hardened tempers are identified by H3x

Recrystallization is characterized by the gradual formation and appearance of a microscopically resolvable grain structure (Fig. 13). The new structure is largely strain free, with few if any dislocations within the grains and no concentrations at the grain boundaries. Recrystallization occurs with longer times or higher heating temperatures than do the recovery effects described in the preceding section, although some overlapping of the two processes is usual. Metallographic studies indicate that the recrystallized grains are formed by the growth of selected subgrains in the deformed and recovered structure (Ref 7).

Recrystallization depends upon time and temperature (Ref 8). Times for the beginning and end of recrystallization in 1100 sheet are shown in

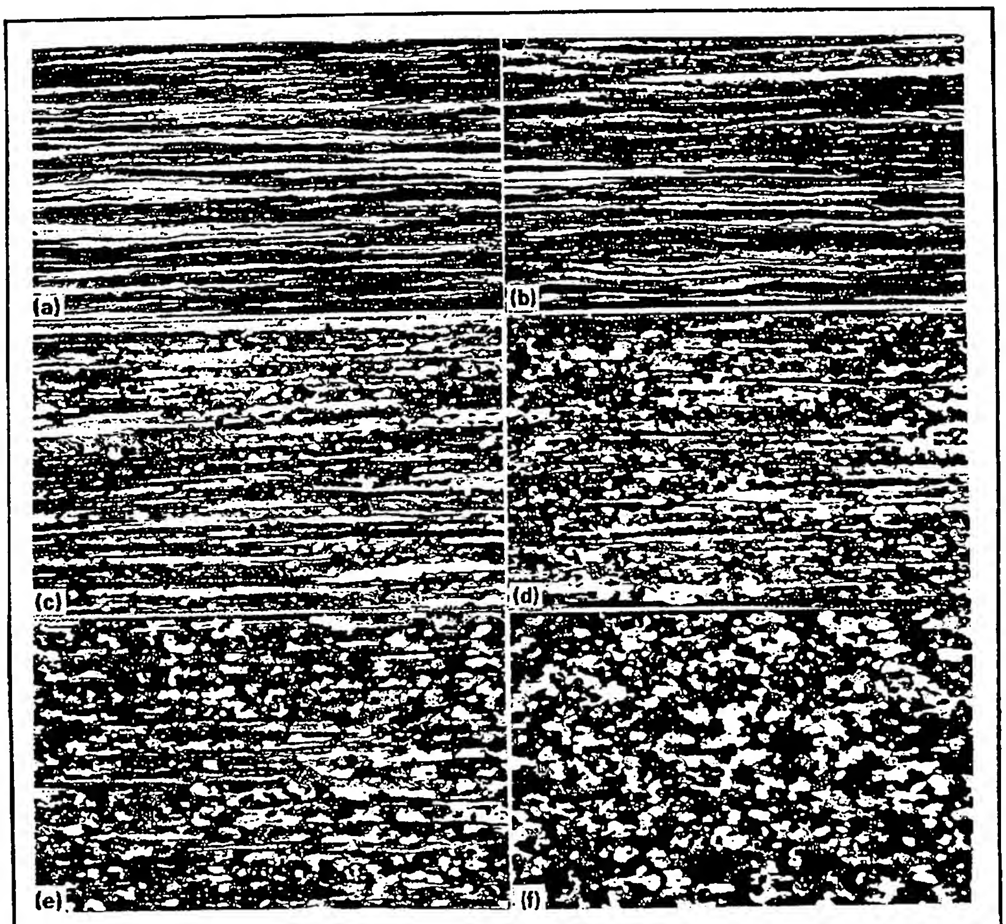


Fig. 13. Polarized light micrographs showing the progress of recrystallization in 5182-H19 sheet anneuled at 245 °C (470 °F); (a) As-rolled; (b) after 1 h at 245 °C (470 °F); (c) after 2 h; (d) after 3 h; (e) after 4 h; and (f) after 7 h. Barkers etch, 120×. (Courtesy of B.A. Dixon, Kaiser Aluminum & Chemical Corp.)

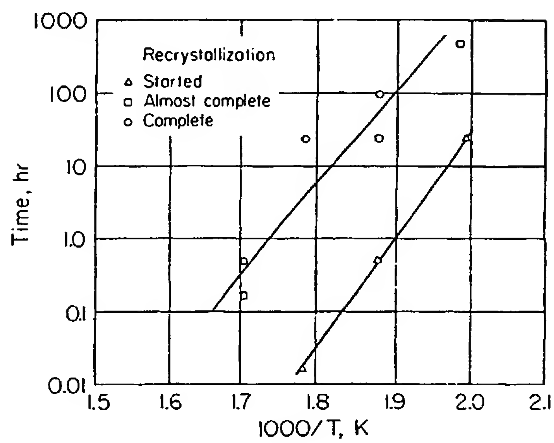


Fig. 14. Time-temperature relations for the recrystallization of 1100-H18 sheet. (Courtesy of Aluminum Company of America)

Fig. 14 as a function of annealing temperature. This relationship can be expressed by a rate equation of the type:

$$\frac{1}{t} = ke^{-a/T} \qquad \text{(Eq 4)}$$

where t is time, T is the absolute temperature, e is the base of natural logarithms, and k and a are material-dependent variables unique to each alloy and its condition. The term a may be replaced by Q/R, where R is the gas constant and Q is an energy term, similar to an activation energy. The magnitude of Q has been reported to be about 214 kJ/mol for commercially pure aluminum (Ref 9). Aluminum alloys generally show good agreement with Eq 4, except when secondary reactions, such as the solution or precipitation of intermetallic phases at annealing temperatures, interfere.

The amount and temperature of working also affect recrystallization. Generally, a greater amount of cold work reduces the time and the temperature for recrystallization. Information on the effects of working temperatures is not precise, but recrystallization becomes more difficult as the working temperature is raised. Alloys worked at temperatures above about 400 °C (750 °F) are usually very difficult to recrystallize.

Composition also influences the recrystallization process. This is particularly true when various elements are added to extreme-purity aluminum; almost any added impurity or alloying element in solid solution raises the recrystallization temperature substantially. When the solubility limit of the added element in aluminum is exceeded, however, the effects on recrystallization can be complex. Dispersed phases in aluminum may act to accelerate or retard the recrystallization process depending on their size, interparticle spacing, and stability at the annealing temperature (Ref 10).

Figure 15 illustrates the change in recrystallization behavior resulting

lute alloys, all the iron is retained in solid solution, and a progressive increase in the recrystallization temperature range occurs with increasing iron. This trend is reversed as further iron additions exceed the solubility limit, and a dispersed ($FeAl_3$) phase appears in the matrix. Further iron additions increase the volume fraction of the dispersed $FeAl_3$ particles, and a corresponding progressive reduction in the recrystallization temperature range is exhibited. The narrowing range of recrystallization temperature can be attributed to enhanced rates of nucleation resulting from the increasing numbers of dispersed $FeAl_3$ particles of 0.6 to 2.2 μm (0.02 to 0.09 mil) diameter (Ref 11).

A regime of particle size (≤0.1 μm or ≤0.004 mil) and interparticle spacing (≤1.5 μm or ≤0.06 mil) exists, in which recrystallization can be inhibited because the dislocation cell structure in the deformed metal becomes anchored and stabilized by the particles (Ref 12). In extreme cases, the recrystallization temperature can be raised to 500 °C (930 °F) or higher (Ref 13). This situation may result in a generally larger recrystallized grain size than usual. However, the ultrafine dispersions required to achieve such high recrystallization temperatures do not normally occur in aluminum alloys fabricated by conventional practices. Extraordinary processing, for example, an extremely fast ingot solidification rate, is necessary to significantly raise recrystallization temperatures above the 340 to 410 °C (645 to 770 °F) range that is typical for commercial aluminum alloys.

The grain size obtained by recrystallization is an important structural feature and is subject to some measure of control. In a given alloy, one of the most important variables affecting grain size is the amount of cold work (Fig. 16). With small amounts of cold work, the grain size obtained on recrystallization is relatively large. As cold work increases, the grain size decreases asymptotically at a rate determined by composition, the fabrication history of the metal, and annealing conditions. For a given history and annealing condition, recrystallization does not occur below a

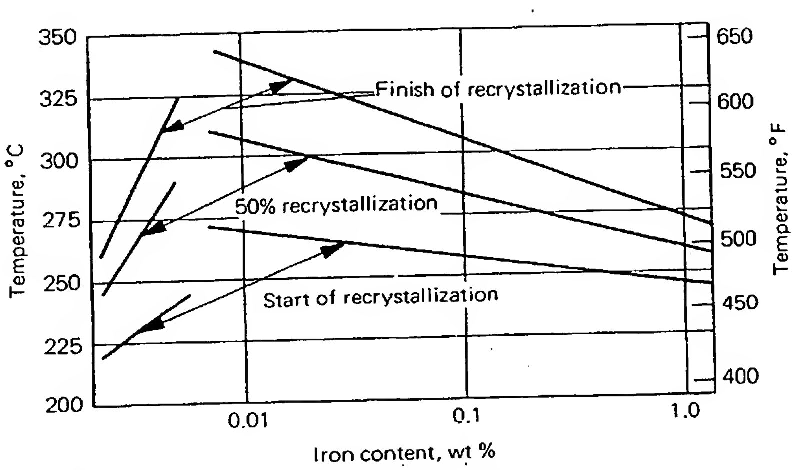


Fig. 15. Isochronal (1-h) recrystallization temperature versus iron content for

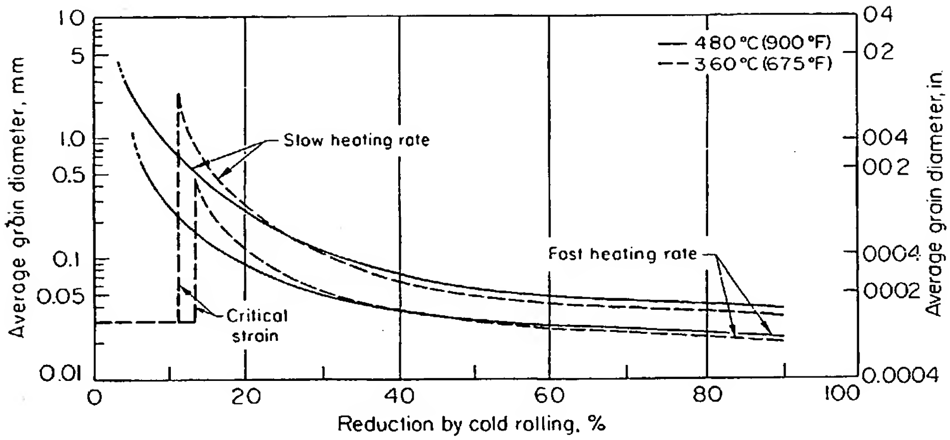


Fig. 16. Grain size of 1100 sheet after annealing at 375 or 400 °C (675 or 900 °F). (Courtesy of Aluminum Company of America)

specific minimum strain. This critical strain produces the largest recrystallized grains under the specified heating conditions.

The rate of heating to the annealing temperature also has a considerable effect on the grain size of aluminum alloys. Figure 16 shows that slow heating produces a much larger grain size than rapid heating. The effects of annealing temperature are also illustrated in Fig. 16. A higher annealing temperature decreases the critical strain at which recrystallization occurs, but it does not significantly change the relationship between grain size and the degree of deformation, or the heating rate.

Many hot worked alloy products, especially those from the higher strength alloys, may resist recrystallization, even when subjected to solution heat treating temperatures. However, large recrystallized grains may be found at a shallow depth below the outer surfaces. One explanation for this is that the working processes are such that deformation is more severe at the outer surface than toward the center (Fig. 17). Thus, an effective strain hardening gradient exists at the completion of working. This effective strain hardening may straddle the critical strain required to produce recrystallization under a given combination of time and temperature. Holding at temperature after hot working or subsequent reheating can produce recrystallization in the surface region that exceeds the critical strain. Under such conditions, the recrystallized grains are very large.

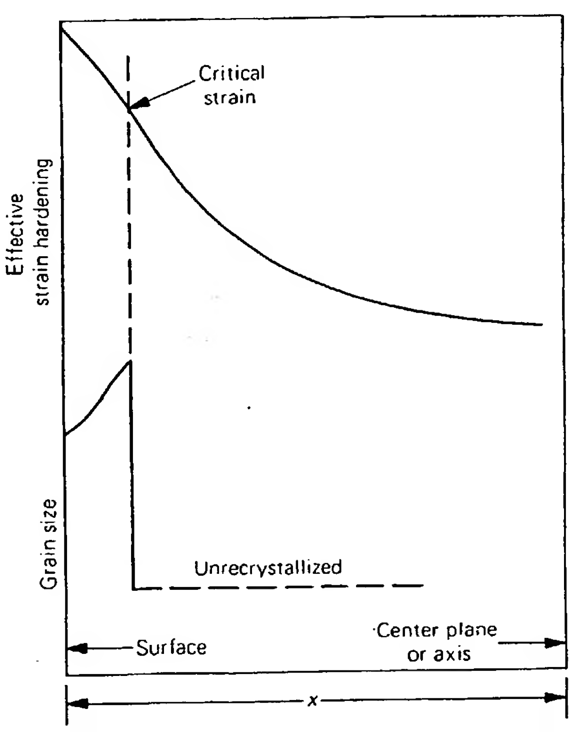
Grain size is also strongly affected by composition. Generally, common alloying elements and impurities such as copper, iron, magnesium, and manganese decrease grain size. The effects of elements of limited solubility, such as chromium, iron, and manganese, are influenced by the compounds they form with each other and with other elements, and by their distribution in the structure. Manganese is particularly notable in this regard (Ref 14). The distribution of such solute elements is determined by ingot casting conditions, by ingot preheating (Chapter 5 in this

trolled commercially to produce a distribution favorable to the formation of a fine grain size.

The recrystallized grain shape in wrought aluminum alloys varies considerably, from nearly equiaxial in commercially pure or low alloyed materials, to very elongated or flattened in highly alloyed materials. The grain shape is influenced mainly by elements such as manganese, chromium, and zirconium. These elements are inhomogeneously distributed in the original cast material and form very fine precipitate (dispersoid) particles, generally in the order of 0.1 μm (0.004 mil), or less. The wrought structure consists of alternating bands or layers of dense or sparse dispersoid. Recrystallizing grains tend to have their growth obstructed by such bands and, therefore, produce the elongated grain shape common to most higher strength alloys.

Recrystallization produces further changes in the properties of the deformed and recovered metal. These continue until annealing and recrystallization are complete. The properties then are those of the original, unstrained metal, except as they are changed by differences in grain size and preferred orientation. In heat treatable alloys, annealing also may be accompanied by precipitation and changes in solute concentration (Chapter 5 in this Volume).

Tensile property changes during isothermal annealing are illustrated in Fig. 11, and the time for the beginning of recrystallization is indicated.



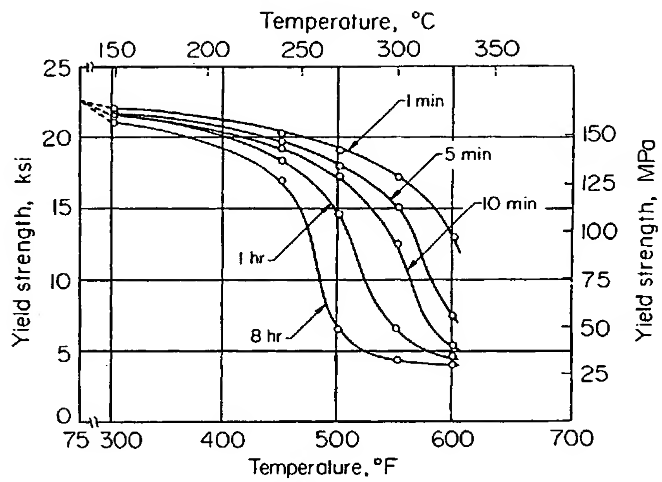


Fig. 18. Annealing curves for 1100-H18 sheet. (Courtesy of Aluminum Company of America)

The relationship between recrystallization and softening is better shown in the isochronal plots of Fig. 18. Here, recrystallization changes the slope of the softening curve and increases the annealing rate. The annealing rate increases approximately exponentially as temperature increases. Annealing occurs at lower temperatures with greater amounts of prior cold work. Recrystallization is also accompanied by a further decrease in stored energy, as measured calorimetrically (Ref 6), as well as by complete elimination of residual stresses.

Grain Growth After Recrystallization. Heating after recrystallization may produce grain coarsening, which can take one of several forms. The grain size may increase by a gradual and uniform coarsening of the microstructure, usually identified as normal grain growth. The process proceeds by the gradual elimination of small grains with unfavorable shapes or orientations relative to their immediate neighbors. This occurs readily in high-purity aluminum and its solid solution alloys and can lead to relatively large average grain sizes. Such grain growth is promoted by small recrystallized grains, high temperatures, and extensive heating. Some grain coarsening of this type also occurs in commercial aluminum alloys, but is greatly restricted by finely divided impurity phases and by intermetallic compounds of elements, such as manganese and chromium, that slow down the process, pin the grain boundaries, and prevent further movement. Figure 19 shows grain growth in recrystallized 1100 aluminum. Some grain growth does occur in very fine-grained sheet, but not to any appreciable extent in sheet with initial grain counts of 200 to 700 grains per square millimeter. Grain counts of this magnitude are typical of most commercially produced 1100-0 alloy sheet.

Aluminum alloys subject to some form of pinning or growth restraint occasionally undergo a different kind of grain growth. This exaggerated grain growth, or secondary recrystallization, proceeds by the growth of

only at very high temperatures and may attain diameters of several millimeters. Apparently, the normal growth-inhibiting effects of elements such as iron, manganese, and chromium are lost or modified at high temperatures, through solution, or through changes in particle size and shape (Ref 15). Because of the high temperatures, the few grains that first lose or overcome these restraints grow rapidly and consume other potential growth centers, and in this manner, a few grains of very large size are formed. In most alloys, high temperatures alone are not the only cause for giant grains. Small primary grain size and well-developed annealing texture are other factors that promote this form of grain growth.

CRYSTALLOGRAPHIC TEXTURE

Rolling Texture. Cast aluminum tends to have a random distribution of grain orientations, except where columnar grains are formed. The random character of the cast structure is rapidly lost during hot or cold working and is replaced by crystallographic textures in which considerable numbers of the deformed grains assume, or approach, certain orientations. Such textures occur because deformation, or slip, in aluminum is confined to certain crystallographic planes and directions. At room temperature, slip occurs on the $\{111\}$ planes in the $\langle 110 \rangle$ directions (Ref 16). Deformation on sets of such planes produces a gradual crystallographic alignment (rotation) of deformed grains into specific orientations with respect to the surface of the workpiece and the direction of working.

The crystallographic texture of sheet can be accurately described by means of x-ray pole figures that are stereographic projections of poles of the $\{111\}$ slip planes (Ref 16). Figure 20 illustrates such pole figures obtained on two heavily cold rolled aluminum sheet alloys. The relative number of poles is indicated by the shading, which gives the concentrations in terms of R, the number of poles to be expected in an ideal metal sample of random grain orientation (Ref 17).

The final textures achieved with large amounts of deformation vary with the nature of the working process, with the changes in shape of the workpiece and, to a lesser extent, with the composition of the alloy.

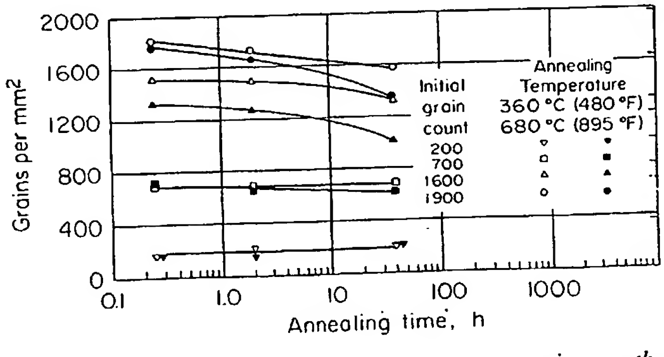


Fig. 19. Effects of annealing time and temperature on grain growth in 1100-0 ... with different initial grain sizes. (Courtesy of Aluminum Company of Amer-